Fermi National Accelerator Laboratory

FERMILAB-Pub-79/76-EXP
7420.180
(Submitted to Phys. Lett.)

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Fermilab-IHEP-ITEP-Michigan University Collaboration

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November 1979

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ABSTRACT

We investigate the net charge in the current fragmentation region in antineutrino-nucleon charged current interactions in the Fermilab 15-Ft. bubble chamber. Support is presented for the d quark origin of the forward hadrons in the hadron center-of-mass system. An extrapolation of the net charge to infinite center-of-mass energy is performed giving as a result $\langle Q \rangle = -(0.44 \pm 0.09)$. Combining this result with the result obtained using our ν events in the same experiment we obtain the value $0.98 \pm .15$ for the charge difference between the fragmenting quarks in ν and $\bar{\nu}$ charged current events.

Jets of hadrons are seen in recent lepton-nucleon and e^+e^- annihilation data[1,2]. It is generally believed that the characteristics of the observed jets are the same both in hadron initiated large transverse momentum processes and in lepton induced processes. In this paper we investigate the net charge of the jet of forward hadrons in the hadron center-of-mass system (current fragmentation region) produced in antineutrino-nucleon charged current events and discuss the possibility that the net charge identifies the original quark.

In the quark-parton picture it is argued that the quark jet resulting from deep inelastic scattering retains some of the quantum numbers of the original quark when averaged over many events[3]. Although the idea of quantum number retention is not a characteristic of all theoretical models,[4] it has been shown that consideration of the space-time developement of the fragmentation process selects the models containing quantum number retention[5]. If we wish to measure the electric charge of the quark we must, however, correct for the charge which "leaks out" from the current fragmentation region through the quark-antiquark pairs created in the fragmentation process (Fig. 1). The leakage is ultimately due to the SU(3) symmetry breaking that is manifested in the suppression of strange quarks over non-strange quarks[6].

The experimental analysis is based on charged current antineutrino events obtained in the Fermilab 15-Ft. bubble chamber filled with a 36% H_2-64% Ne atomic mixture exposed partly to a double-horn focused wide-band beam and partly to a bare target sign

selected antineutrino beam. The incident proton energy was 400 GeV. The antineutrino energy distribution peaks at 18 GeV and extends to about 200 GeV. About 23,000 events were detected and fully measured in this experiment. Muons were identified by the External Muon Identifier supplemented by a large-transverse-momentum procedure leading to an over-all muon identification of 92% independent of angle for muons with momentum greater than 4 GeV/c.[7] Special attention was given to the determination of the charge and momentum of hadron tracks which were difficult to measure. For tracks interacting or decaying in too short a distance to give an adequate momentum estimate or charge determination the momentum and charge were determined from the tracks emerging from the secondary interaction or decay.[8]

On the average, about 17% of the hadronic energy escapes detection in the bubble chamber and is corrected statistically.[9] The event sample was required to (a) have a muon with positive charge and momentum greater than 4 GeV/c, (b) to be in a restricted fiducial volume ($\sim 17 m^3$) and (c) to have a total momentum along the antineutrino direction larger than 7.5 GeV/c. The number of antineutrino charged current events passing these criteria is 7200 events.

To study the net charge in the current fragmentation region for valence quarks additional data cuts are needed. To reduce the diluting effects of the sea quarks we require $x=-q^2/2p\cdot q>0.1$ (p and q are the target and current four-momenta, respectively). In order to obtain a reasonable rapidity interval between the target and current fragments (which requires $\ln W^2 - \ln(-q^2)$ large) we choose the hadron center-of-mass energy $W>3$ GeV and $-q^2>1$ GeV^2. The final sample passing these criteria is about 2000 antineutrino charged current events.

At finite energies there is in general an overlap between the current and target fragmentation regions. With increasing center-of-mass energy, the overlap decreases but never disappears. The unavoidable contamination at finite W values in the overlap of the fragmentation regions can be treated by a procedure proposed by Field and Feynman.[10] In this procedure one sums the integer charges (+1, -1) with a weight which gradually decreases when the overlap region is approached and one thereby picks up the residual charge from the forward end of the current fragmentation region, i.e. the weighted charge is defined as $Q_W = \Sigma_i z_i^p q_i$, where p is a small number, q_i is the (integer) charge of the i^{th} hadron in the final state and $z=p\cdot h/p\cdot q$ is the fractional momentum of the hadron (h is the hadron four-momentum). Thus tracks at large z where the overlap is expected to be smallest will have a large weight while tracks at small z where we expect overlap to be large will have a small weight. Figure 2 shows our weighted charge distribution and curves for u- and d-quarks from Ref. 10 for p=0.2 and p=0.5. From the general agreement of the data with the d-quark curves (and lack of agreement with u-quark curves) we conclude that the observed current jet results from d-quark fragmentation.

The contribution from the overlap region tends to decrease the net charge in the current fragmentation region. To separate the current and target fragmentation regions. We will, from hereon, consider only charged particles with positive rapidity, $Y^* = 1/2 \ln((E^* + p^*_\parallel)/(E^* - p^*_\parallel))$, where $p^*_\parallel$ is the hadron momentum along the current direction, and E^* is the hadron energy in hadron center-of-mass system. Note that this criteria removes slow protons, which are primarily due to nuclear rescattering processes. Fig. 3 gives the net forward charge of the hadrons, $\langle Q\rangle = \Sigma(N^+ - N^-)/N_{ev}$, as a function of rapidity in three different center-of-mass energy intervals. The total net charge per event summed over the positive rapidity region is also given in Fig. 3. These total net charges are $-(0.14\pm0.04)$, $-(0.24\pm0.04)$ and $-(0.35\pm0.06)$, respectively, for W intervals of 3-4, 4-6 and 6-15 GeV. As we expect, when W increases, the current and target fragmentation regions separate and the net charge in the current fragmentation region increases.

As previously discussed one should have infinite W to see the pure quark net jet charge. We have used the theoretical suggestion (which is well verified in hadronic experiments) that the tails of the net charge distribution are of the form $\exp(-\lambda|\Delta Y|)$ to extrapolate our results to infinite W. Here Y is the rapidity interval available ($\Delta Y_{max} \propto \ln W^2$) and λ is related to the correlation length between the final state particles in the central rapidity region. Previous measurements have obtained $\lambda \sim 1/2$.[11] We have also determined the parameter λ from our data and obtained a result $\lambda = -(0.48 \pm 0.12)$. This indicates that the two-particle correlations are similar in the lepton produced jets and in hadron produced jets. The proper extrapolation variable therefore should be W^{-1}. In Fig. 4 the total net charge[12] per event as determined in the same way as in Fig. 3 is presented as a function of W^{-1}. The extrapolation to infinite W gives a value for the net charge $\langle Q \rangle = -(0.44 \pm 0.09)$ for the hadrons in the current fragmentation region. As a comparison, the shaded region in Fig. 4 shows the prediction for the W^{-1} dependence of the net charge given by an uncorrelated Monte Carlo model.[13]

It was originally proposed by Feynman that quark charge is absolutely retained amongst the current fragments.[3] Then Farrar and Rosner pointed out that there was a charge leakage due to the SU(3) symmetry violation in the $q\bar{q}$-sea. In this framework then, the net charge is related to the quark charge, e_q, and the leakage term[4] by $\langle Q \rangle = e_q - L$. To extract e_q we must know the leakage term. Unfortunately, this leakage term depends on some a priori knowledge of the quark charges. For example, L can be written as $L = \Sigma_i e_q p_i$ where i runs over all quark flavours, e_i is the i^{th} quark charge, p_i is the relative probability to find a quark i from the vacuum. If we assume only u, d and s quarks then by probability conservation $p_u + p_d + p_s = 1$ and by isospin symmetry $p_u = p_d = p$. Assuming conventional quark contents of the π^+- and K^+-mesons gives $\langle Q \rangle = e_q - p - e_d$. Thus for an u-quark jet $\langle Q \rangle = 1-p$ and for a d-quark jet $\langle Q \rangle = -p$. Our value $\langle Q \rangle = -(0.44 \pm 0.09)$ gives $p = 0.44$ for a d-quark jet. This

value is consistent with the value 0.40 ± 0.12 obtained from two independent measurements, one using K^+/π^+ -ratio extrapolated to $x_F = +1$ [14] and the other using the ratio of $(J/\psi \to \rho\pi)/(J/\psi \to K^+K^*)$. Our measurement of $\langle Q \rangle$ is thus consistent with the assumption that the fragmenting quark is a d-quark. The assumption that the fragmenting quark is an u-quark, on the other hand, gives the unacceptable value $p = 1.40 \pm 0.09$.

Finally, if we combine $\langle Q \rangle$ from neutrino and antineutrino data we can write $\langle Q \rangle_{\bar{\nu}} - \langle Q \rangle_{\nu} = e_q - e_{q'}$, where $e_q(e_{q'})$ is the charge of the fragmenting quark from antineutrino (neutrino) interactions. This last expression is independent of the leakage term and gives a measurement of the charge difference $e_q - e_{q'}$, independent of meson quark assignments. By using the neutrino events contained in this exposure (See Fig. 4) to determine $\langle Q \rangle$ we obtain $e_q - e_{q'} = 0.98 \pm 0.15$ which is consistent with the charge assignment of -1/3 for the q' quark and 2/3 for the q quark.

One of us (R.O.) wants to thank H. I. Miettinen for numerous discussions and advice concerning the charge extrapolation method.

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[8] 3.4% of the tracks have the relative error in momentum, $\Delta p/p$, larger than 40%. After the measured secondary interactions and decays are used to estimate the momentum this number decreases to 2%.

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[12] We have investigated possible sources of systematic uncertainties in the jet net charge caused by nuclear rescattering processes and by the energy correction procedure. Nuclear rescattering can generate excess hadrons which can lead to a shift in the observed net charge, Q_v. A cut $-2 \leq Q_v \leq 1$ has been applied to the data. If we remove this cut the extrapolated net charge changes by 5% and

the weighted charge by 10%. We have studied the effect of the statistical energy correction method by redoing the analysis using an event-by-event correction (G. Myatt, CERN/ECFA 72-4, 11 (1972)). From this study we conclude that the uncertainty due to the energy correction procedure is 10% for the extrapolated net charge and 15% for the weighted charge. All of the above uncertainties have been included in the presented errors.

[13] The hadronic states are generated, for a given W, according to longitudinal phase space for produced mesons. The Monte Carlo events are constrained to conserve energy, momentum and charge, but there are no particle-particle correlations built in. The numbers of negative pions to be produced are constrained to follow the parametrisation $\langle n^- \rangle = -0.25 + 0.76 \ln W^2$ evaluated for our data (J. P. Berge et al., Phys. Rev. D18, 3905 (1978)). A complete description of the Monte Carlo program is given in J. Bell et al, Phys. Rev. D19 1 (1979). For this analysis the program was modified to take into account the nuclear target (Fermi motion) and different beam spectrum.

[14] We extrapolate to Feynman-x value of one to avoid complications due to the resonance production at moderate x_F-values. The extrapolated value for the π^+/K^+ then gives a direct measure of the relative abundances of non-strange and strange quarks (R. D. Field and R. P. Feynman, Phys. Rev. D15, 2590 (1977).). The data is from J. Singh et al., Nucl. Phys. B140, 189 (1978) and R. Johnson et al., Phys. Rev. D17, 1292 (1978).

[15]The two decay modes of J/ψ, $J/\psi \to \rho\pi$, K^+K^*, provide an alternative way of determining the SU(3) symmetry violation by measuring the u/s-ratio. Using data from G. J. Feldman and Martin L. Perl, SLAC-PUB-72 (1977), corrected for phase space factors, we obtain u/s = 2.04+0.38.

[16]The ν-component in our $\bar{\nu}$-beam is $\sim$15% averaged over the energy spectrum E > 10 GeV. We select μ^- using both EMI and a kinematic method. With the cuts F_ν > 7.5 GeV, p_μ > 7 GeV/c we obtain $\sim$1000 ν charged current events.

FIGURE CAPTIONS

Figure 1: Quark-parton picture of deep-inelastic lepton-nucleon scattering. The weak charged current (-q) is absorbed by one of the partons in the nucleon. The struck quark emerges with a great velocity relative to the remaining group of nucleon constituents and a colour field is created. Vacuum polarization generates quark-antiquark pairs which in turn combine into the observed particle states. One should note that any kinematic selection to extract the current jet (as indicated by the dotted line) is made to the particles observed in the chamber and a "leakage" of one average quark thus results.

Figure 2: Weighted jet charge distributions Q_w with two values of the weight p (a) p=0.2 and (b) p=0.5. Dotted and solid lines represent predictions of Field and Feynman for d- and u-quark jets, respectively. To compare with the predictions the events are required to have W greater than 6 GeV.

Figure 3: Net charge of the hadrons forward in the hadron center-of-mass system as a function of rapidity for different W intervals. The average net charge per event is (a) -(0.14±0.04), (b) -(0.24±0.04) and (c) -(0.35±0.06).

Figure 4: Extrapolation of the net charge of the hadrons going forward in the hadron c.m.s to infinite W as a function of W^{-1}. Dotted line is a fit to the data above W>3 GeV. Extrapolation gives for the average jet net charge at infinite W $-(0.44 \pm 0.09)$ for $\bar{\nu}$-jets and $+(0.54 \pm 0.12)$ for ν-jets. Shaded region represents the Monte Carlo calculation described in Ref. 13.

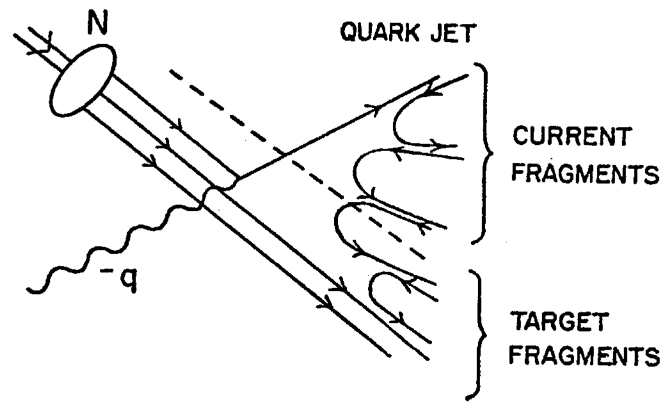


Figure 1

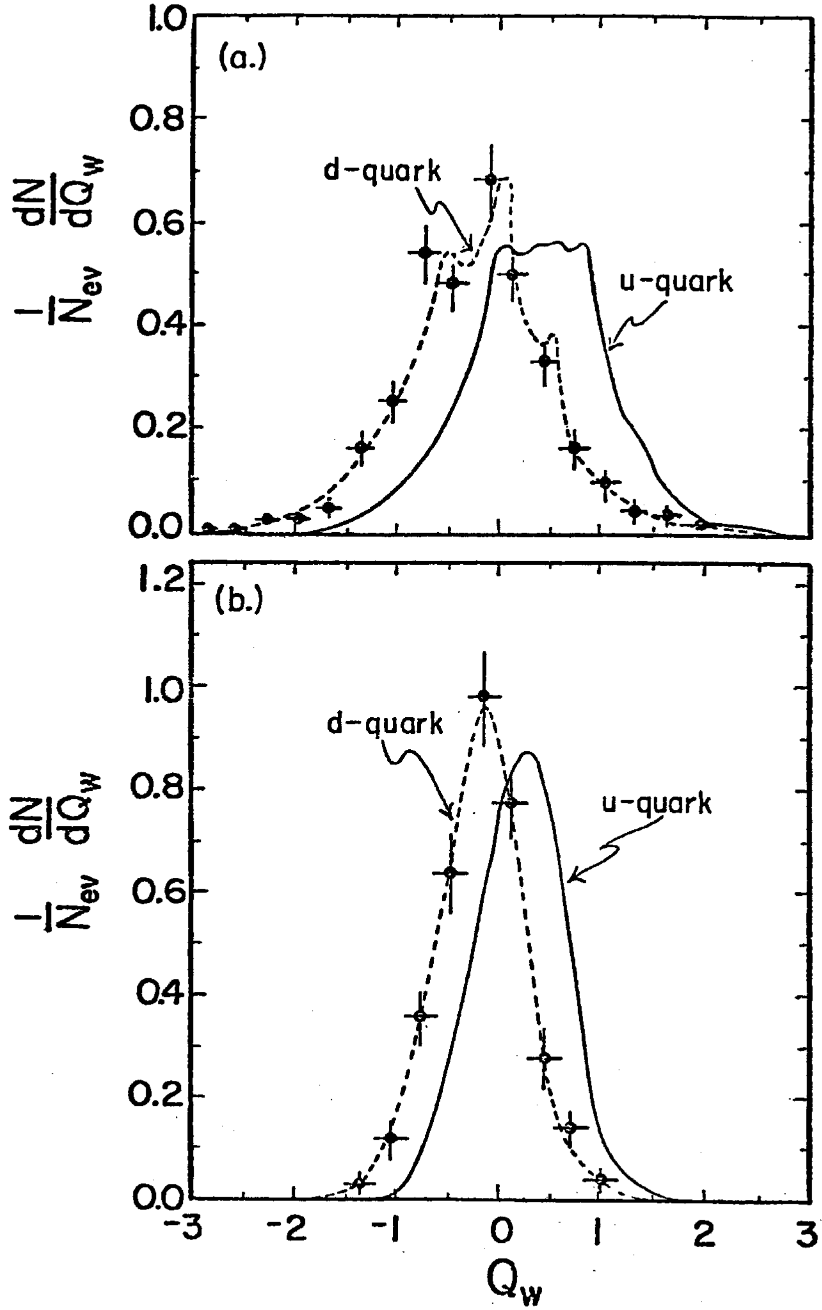


Figure 2

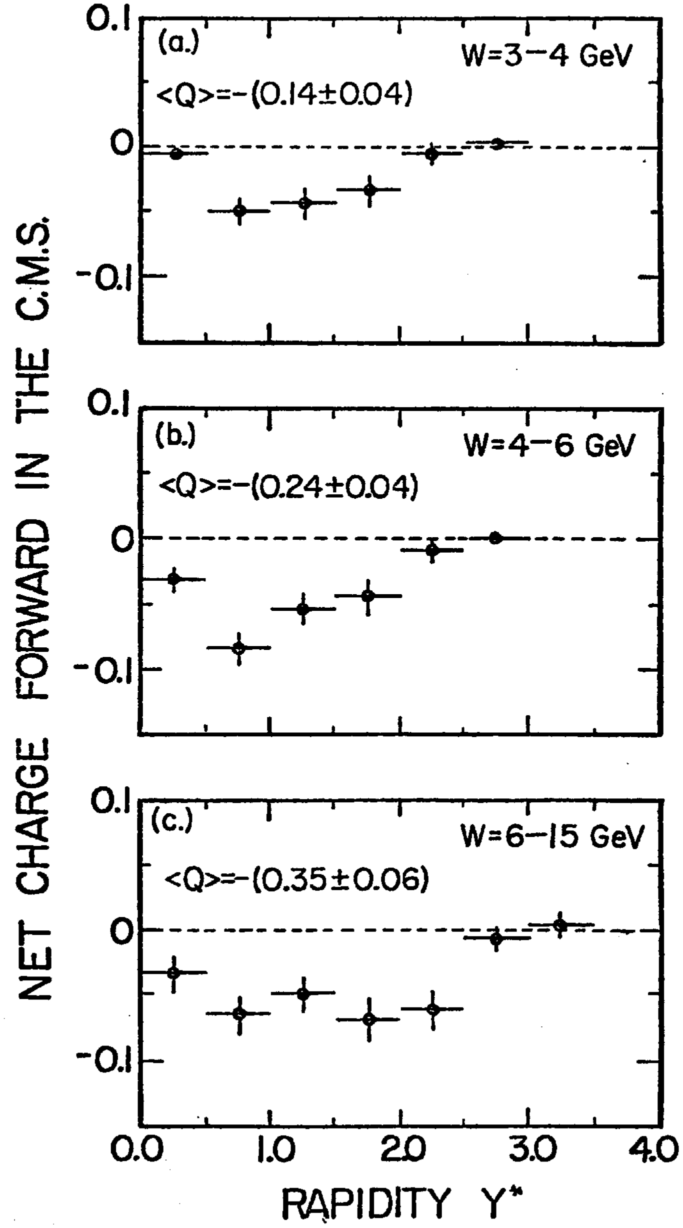
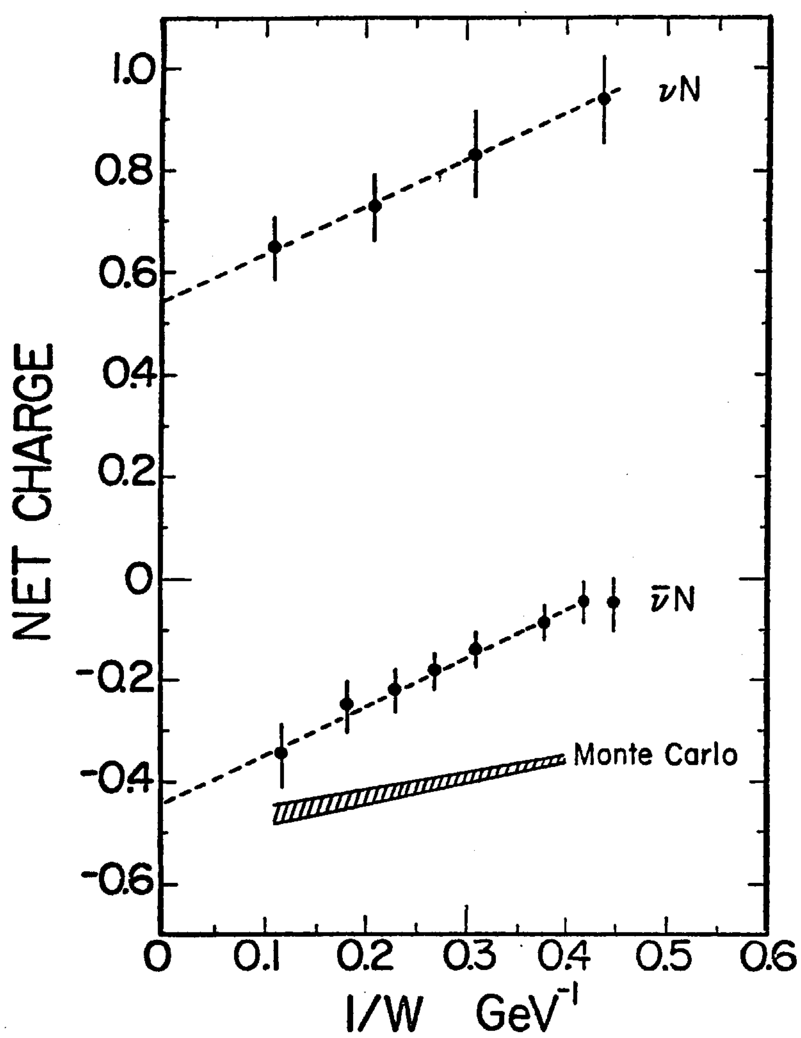


Figure 3


NET CHARGE
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0.5
0.6
1/W GeV^{-1}
νN
$\bar{\nu}$N
Monte Carlo

Figure 4